Reciprocating Engine Technology - Can We Get There From Here?

Timothy J. Callahan

Southwest Research Institute

Reciprocating Engines Peer Review

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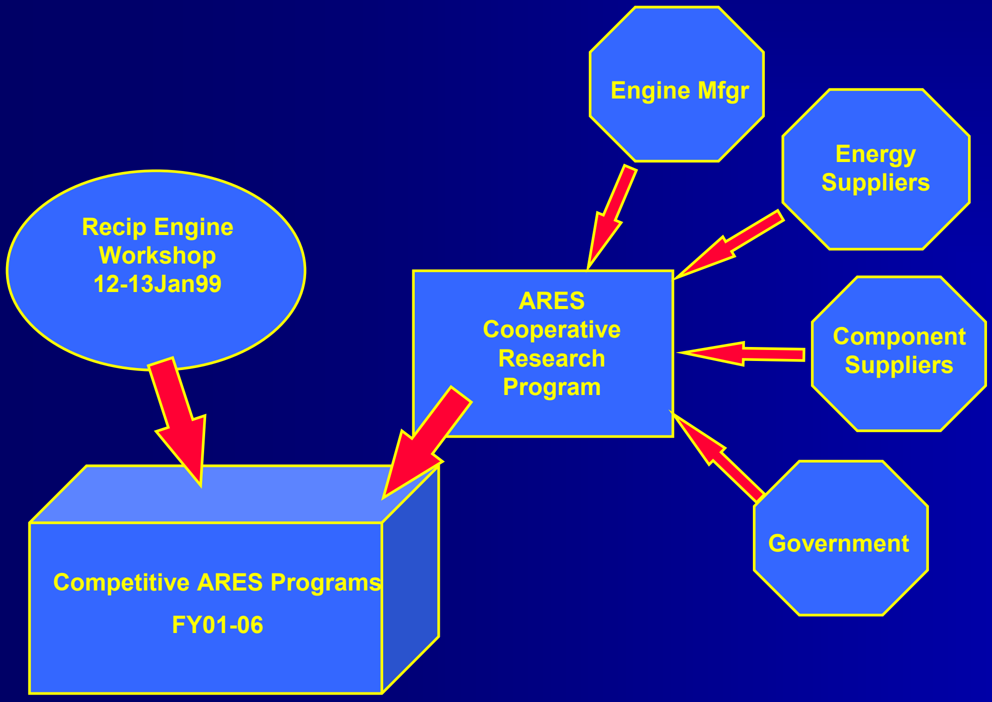
Presentation Outline

- Background
- Objective
- Approach
- Technical Barriers
- Technology Solutions
- Pathway to High Efficiency
- Summary

Background - Advanced Reciprocating Engine Systems (ARES)

ARES was formed (1998) as a cooperative research program with funding from industry and government.



Program Structure

ARES Program Members

Department of Energy (OPT and NETL)
Gas Research Institute (now GTI)

Caterpillar Inc Engine Division
Cooper Energy Services
Cummins Engine Company
Waukesha Engine Division

Southern California Gas
Altronic Inc
Federal Mogul - Champion
Woodward Governor

SwRI ARES Objective

- Identify enabling technology for development of high efficiency, low emission, stationary natural gas engines (nominal power ~ 1 MW)
- Efficiency target: 50% Brake Thermal Efficiency
- NO_x emissions target: 0.1 g/hp-hr

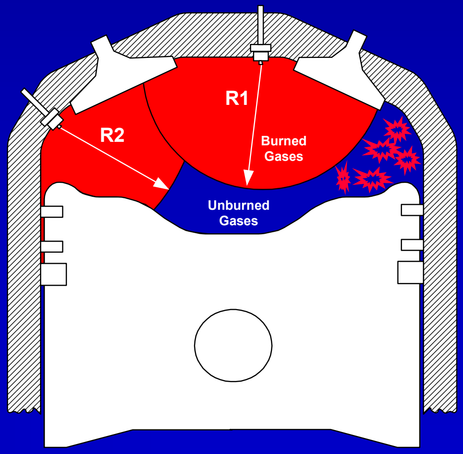
Program Approach

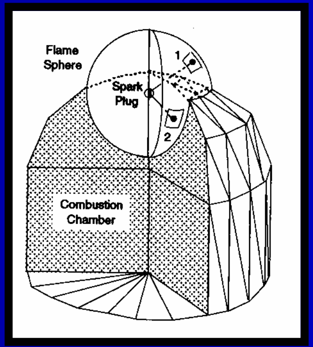
Single Cylinder CAT3501 Research Engine

- Modeling and simulation to identify technical paths and barriers
- Bench scale and single cylinder engine testing to evaluate various technologies
- Evaluation of potential combustion systems
  - Miller Cycle
  - Micro-pilot open chamber
  - Combustion of dilute mixtures
  - Direct water injection
  - Multiple-site ignition

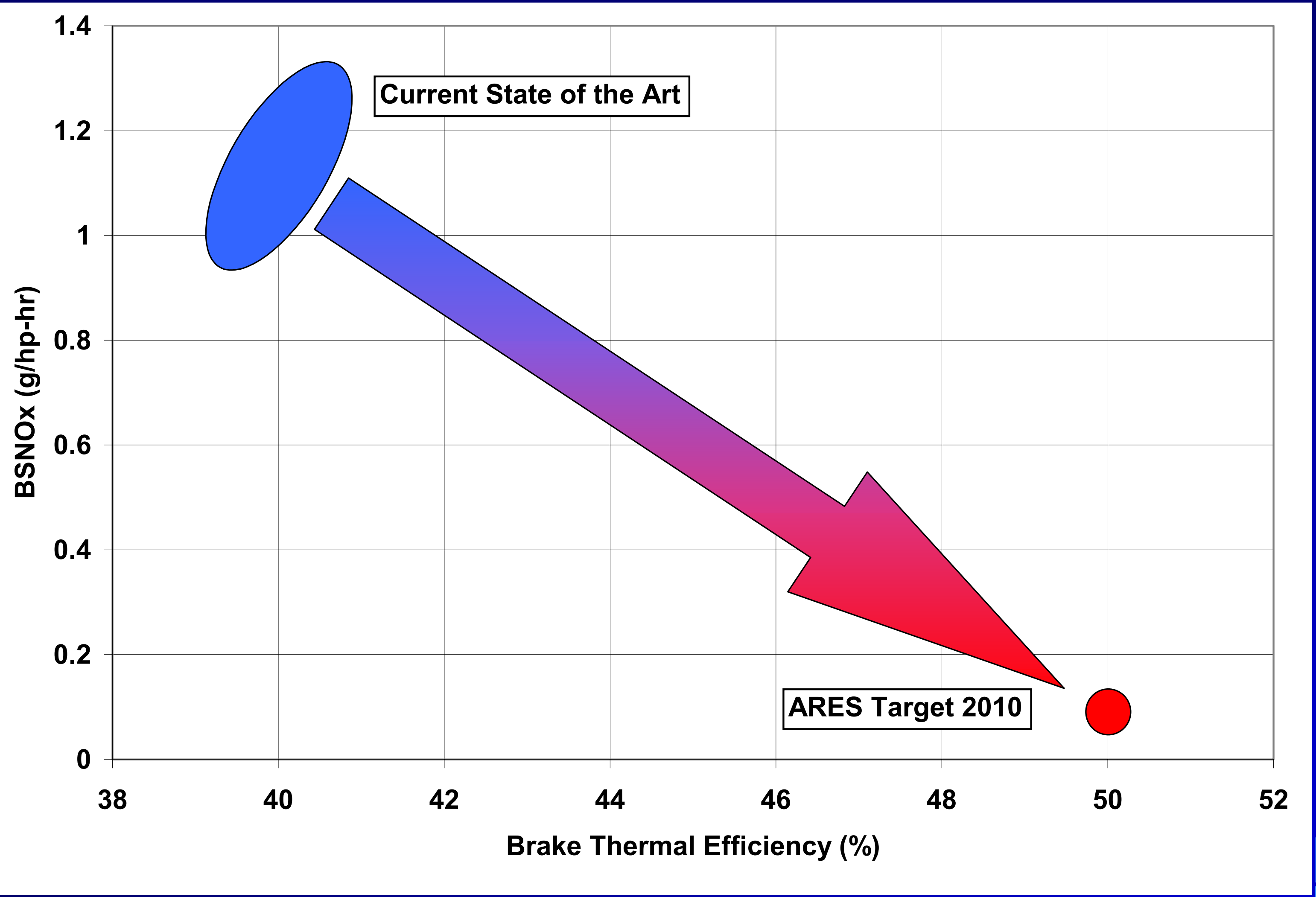
Approach - Simulation Tools

- **ALAMO_Engine:**
  - Zero-dimensional cycle simulation model used for predicting efficiency and NO_x emissions
  - Calculates equilibrium products of combustion
  - Combustion is two zone, burned and unburned
- **RPEMS - Rapid Prototyping Engine Modeling System**
  - Combustion chamber design analysis tool used for burn rate and knock prediction
  - Extended for simulation of large-bore, natural gas engines
- **GT Power**
  - Commercially available cycle simulation code

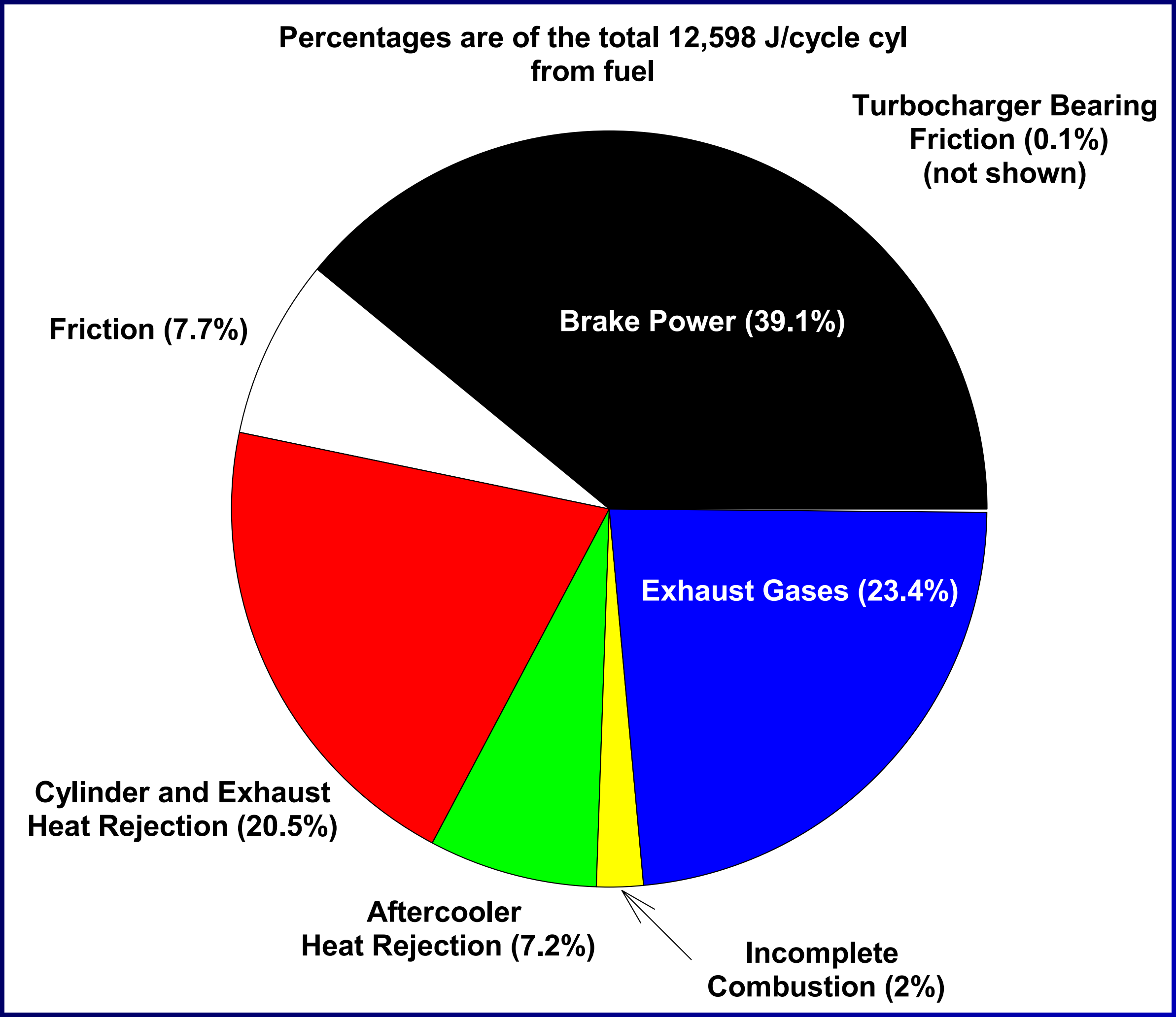




"Can we get there from here?" Where is here?



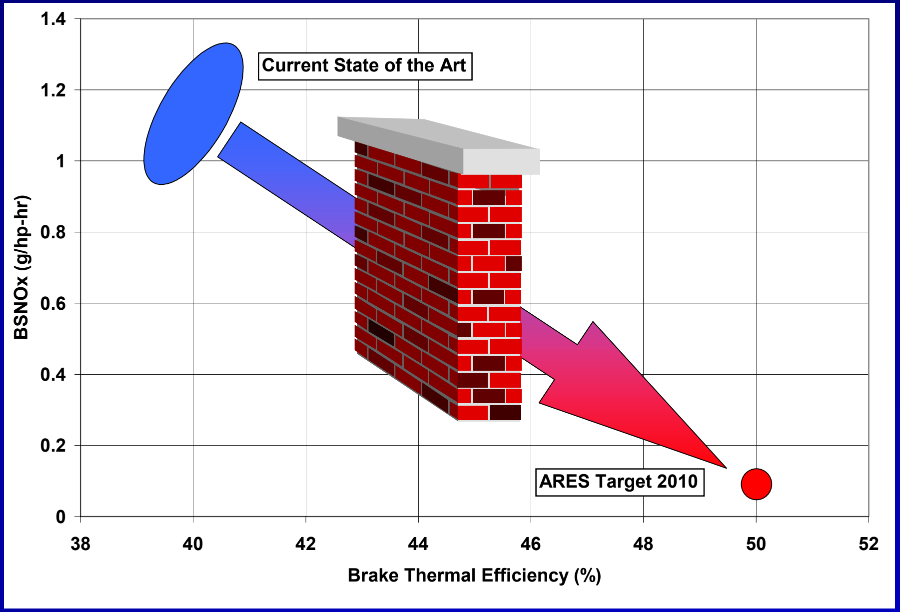
Baseline Engine Energy Balance



- Typical efficiency near 40% at 1 g/hp-hr NO_x
- Energy losses include
  - Heat transfer
  - Friction
  - Exhaust energy
  - Unburned Fuel

Known Barriers to High Efficiency for Natural Gas Combustion

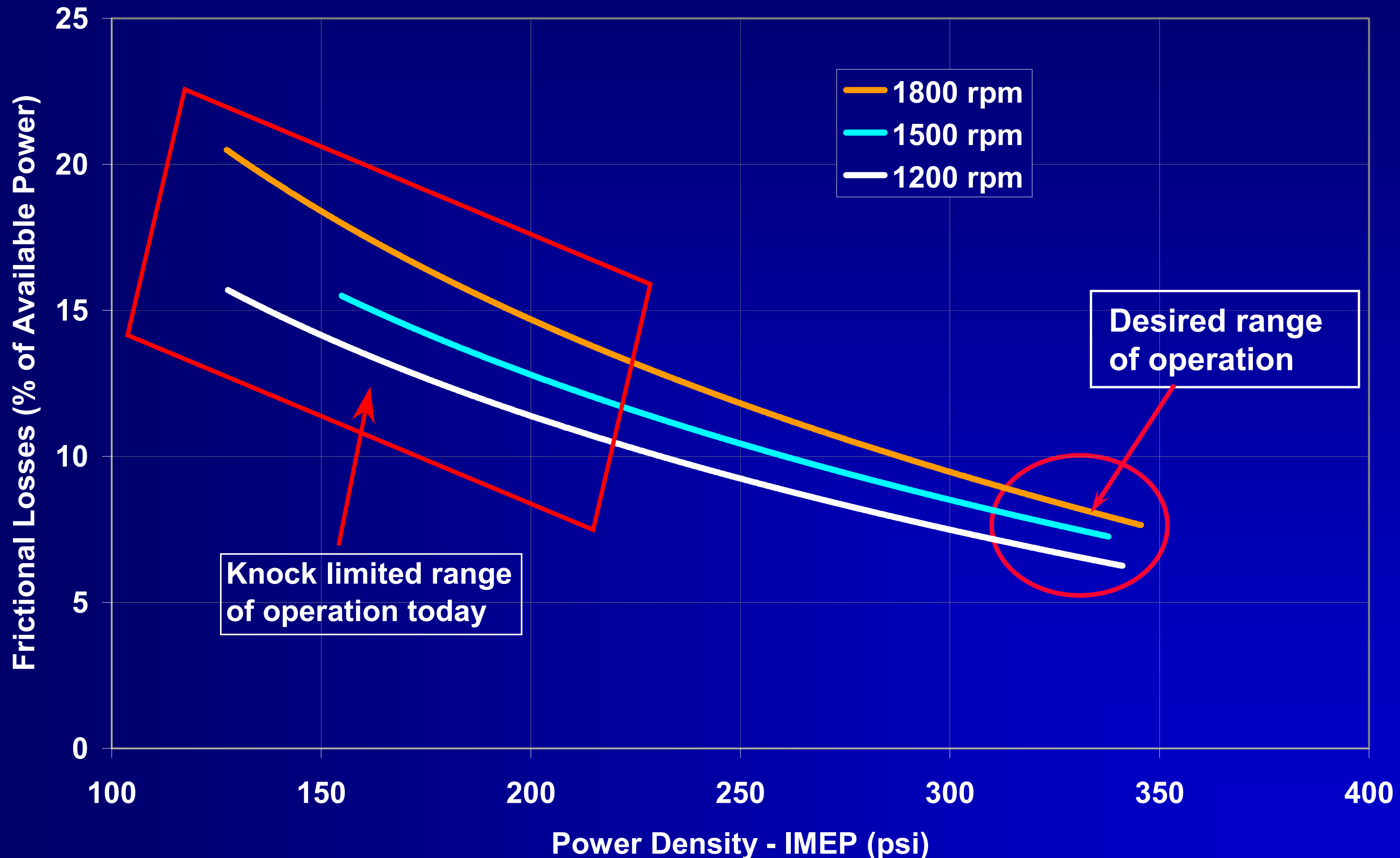
- Knock (uncontrolled combustion)
- NO_x emissions
- Structural limitations
- Combustion efficiency (unburned fuel)
- Combustion rate (slow reactions at low temperature)
- In-cylinder heat loss
- Frictional losses
- Pumping losses
- Exhaust port and manifold heat loss
- Inefficient exhaust energy recovery



ARES Technologies

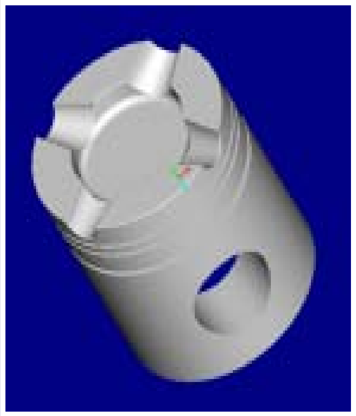
- Combustion Chamber Geometry
- Combustion of Dilute Mixtures
- Modified or Alternative Engine Cycles
- Exhaust Aftertreatment LNC, TWC, SCR
- Water Injection
- High Power Density
- Multiple Source Ignition
- Exhaust Energy Retention
- Turbo-compounding
- Friction Reduction

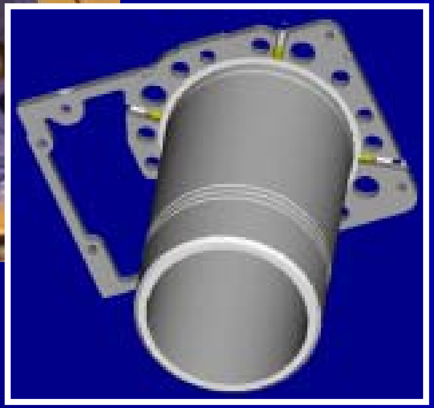
Increased Power Density



- Higher power density leads to a reduction in frictional losses

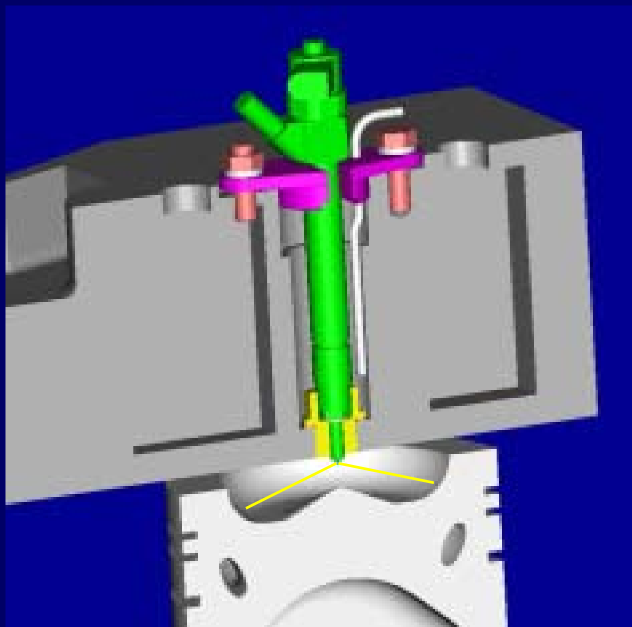
Multiple Site Spark Ignition



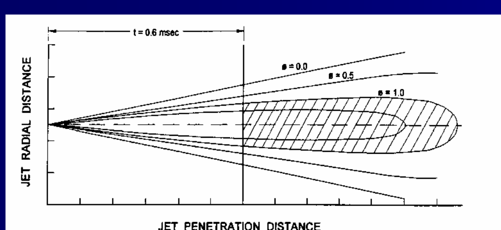


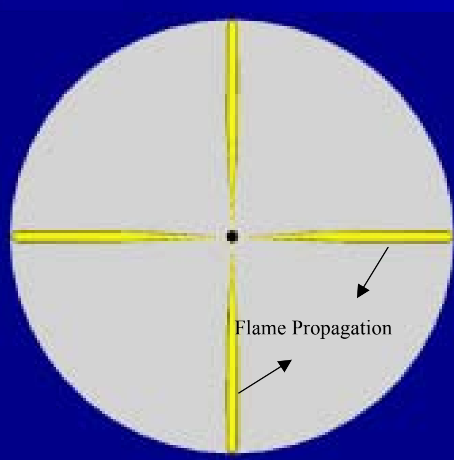
- Combustion, initiated at multiple sites, proceeds from periphery toward center
- Faster combustion rates and elimination of end gas regions prone to knock
- Improved
  - misfire limit
  - reduced knock tendency
  - shorter combustion duration
  - higher combustion efficiency
  - higher BTE

Pilot Ignition also a Multi-Site Ignition Concept

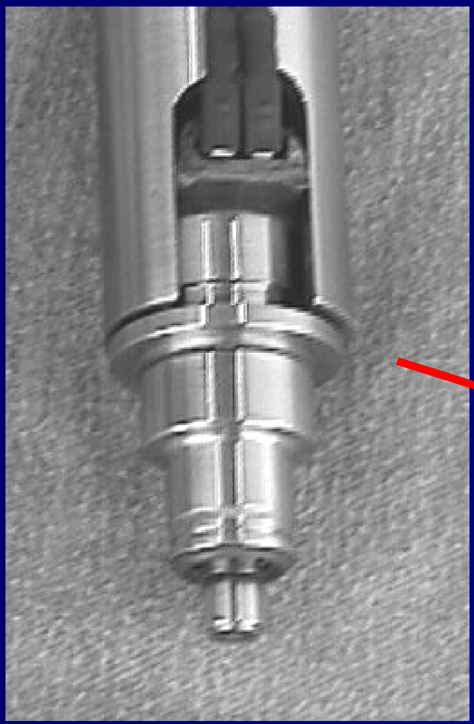


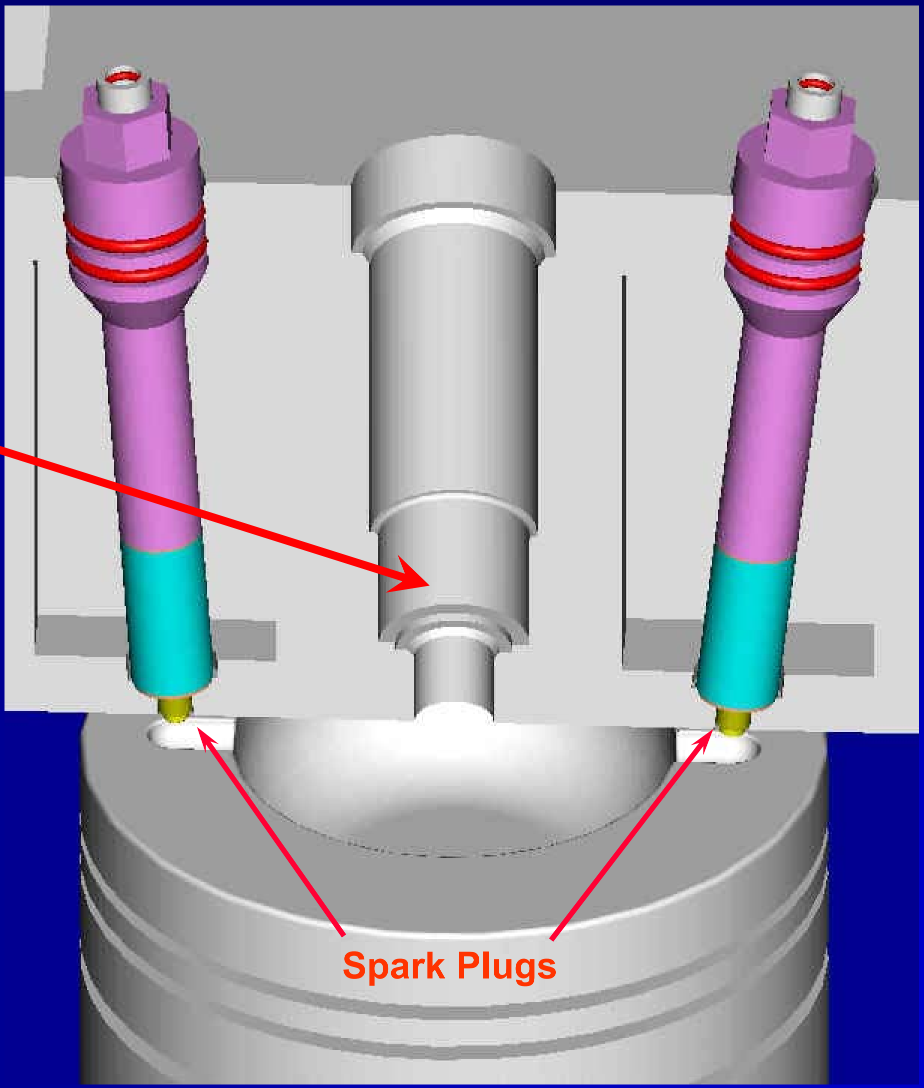
- Diesel fuel penetrates the combustion chamber prior to ignition
- High pressure enables good penetration
- Injection pressures of diesel injection systems now approaching 30 ksi
- Improved
  - misfire limit
  - shorter combustion duration
  - higher combustion efficiency
  - higher BTE





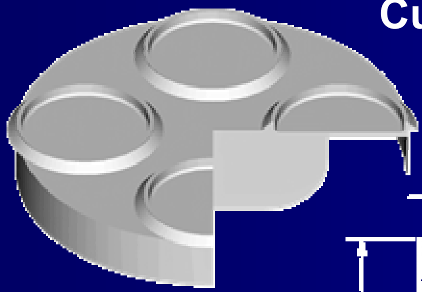
Simultaneous Knock and NO_x Mitigation: Direct In-cylinder Water Injection



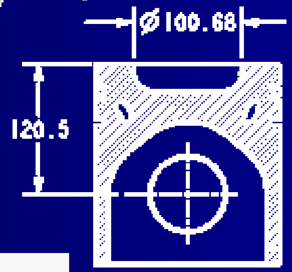


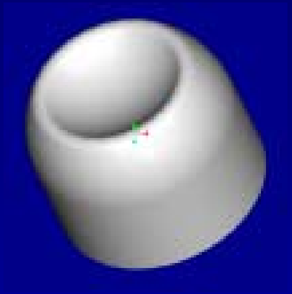
Water injection used to lower in-cylinder temperatures reducing potential for knock and NOx formation

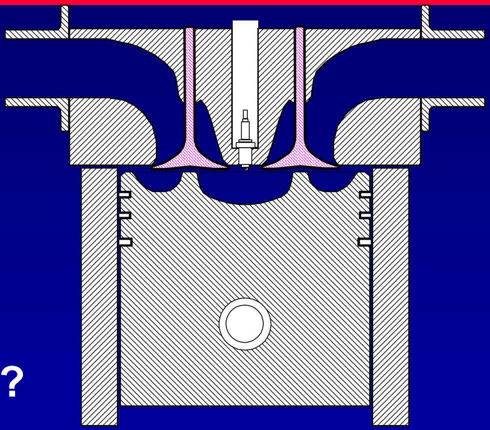
Combustion Chamber Evolution

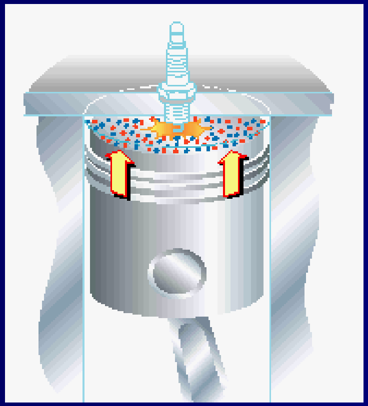


Current technology

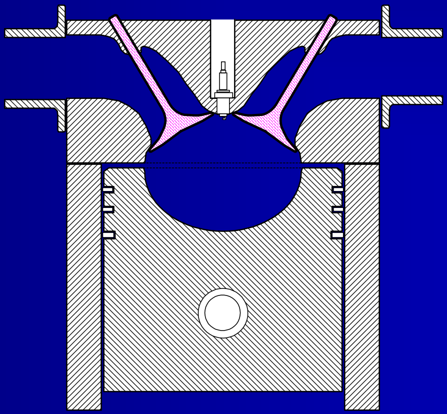








Future ?



- Appropriate design of combustion chamber required for
  - Complete combustion of dilute mixtures
  - Knock tolerance

Aftertreatment

- Lean NO_x catalyst (LNC)
  - Currently not a viable technology
- Selective catalytic reduction (SCR)
  - Viable for lean combustion, requires reductant (typically urea) that adds to operating costs
  - Potential for ammonia slip, control issue
  - 90-95% efficiency
- 3-way catalyst if no oxygen present in exhaust stream
  - Proven in light duty, shorter life applications
  - Low capital cost relative to SCR
  - 95-99% efficiency

Pathway to High Efficiency and Low Emissions

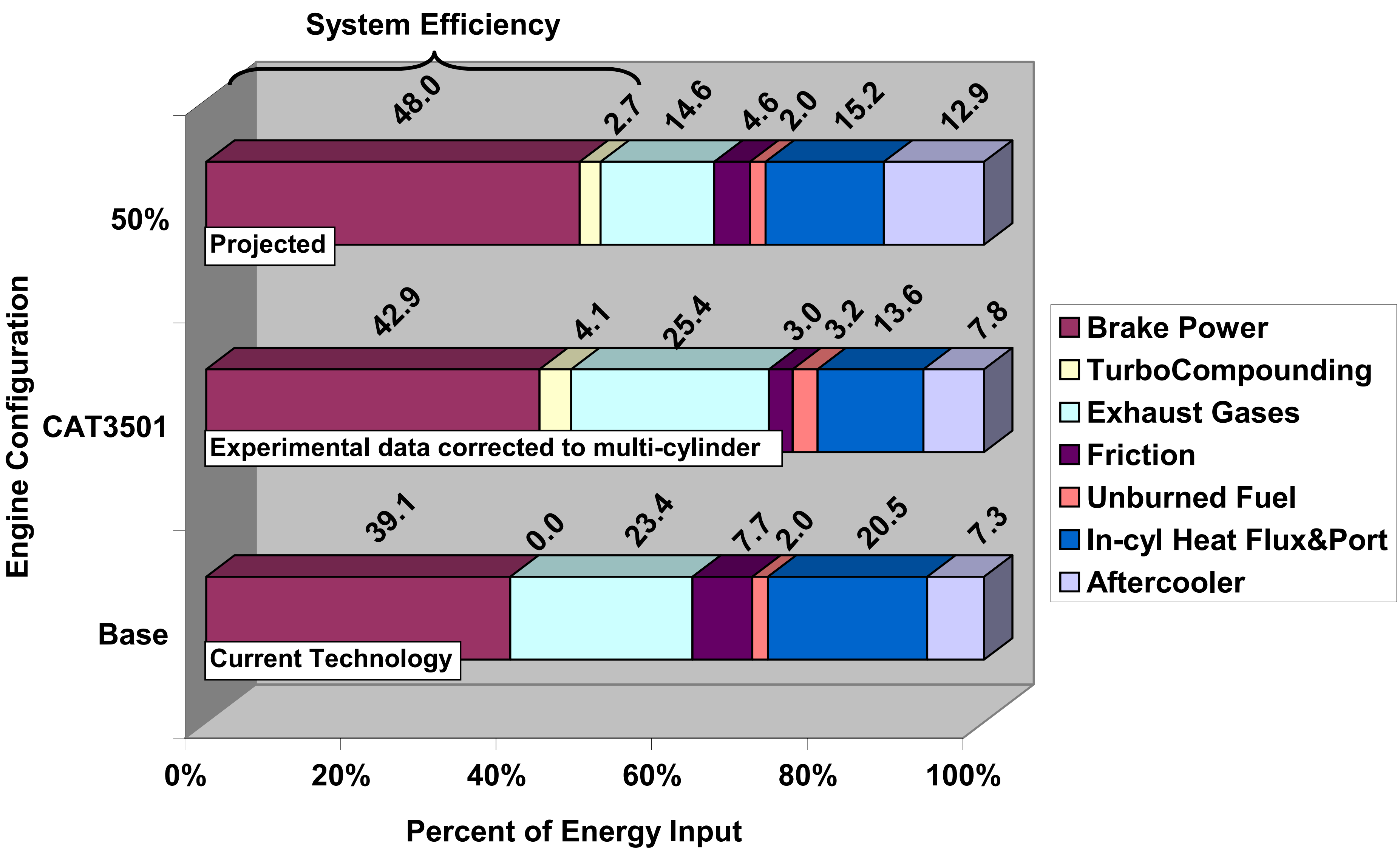
- High efficiency will require higher power density (BMEP)
- Knock limitations must be overcome to achieve higher BMEP
- Aftertreatment required
- Low NO_x requires dilute air-fuel mixtures - two alternatives
  - Dilute with excess air - requires aftertreatment technology to reduce NO_x in presence of oxygen (SCR)
  - Dilute by recirculating exhaust gases (EGR) - can use 3-way catalyst for NO_x reduction in “zero” oxygen exhaust stream
- Ignition and combustion of dilute mixtures a necessity
  - Multiple-site ignition
  - Distributed combustion
- Exhaust energy retention for turbocharging is a key technology
- Minimized parasitic losses (friction, pumping, etc)

Multiple technologies will be required to achieve both efficiency and emissions goals!

Improvements Required for ARES Engine

Parameter	*Current Technology*	*ARES Technology*
Power Density (BMEP)	170-200 psi	350 psi
Peak Cylinder Pressure	1500-1800 psi	3200 psi
Turbocharger Efficiency	56 %	65+ %
Mechanical Efficiency	87-89 %	91+ %
Combustion Rate	25-30 Crank Angle Degrees	15-18 Crank Angle Degrees
Aftertreatment	No	Yes
Turbocompounding	No	Likely

Energy Balance for Base Engine, CAT3501 Test Engine, and 50 Percent ARES Engine

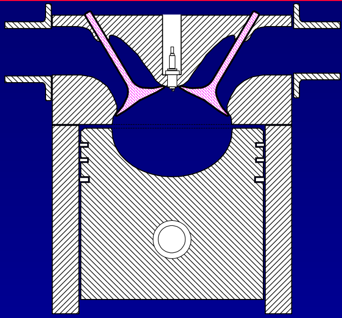


Summary of Expected Gains for 50% Efficiency - Can We Get There From Here?

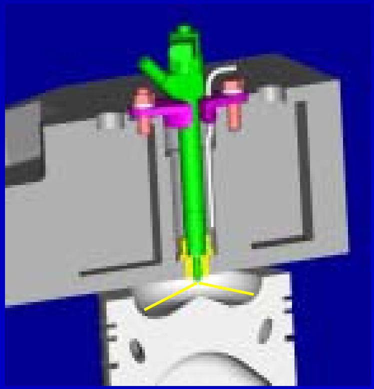
	Description	Contribution (BTE points)
Miller Cycle	1.5 Expansion Factor	~ 1.7 points
Turbo-Compounding	80% turbine efficiency 95% gear train efficiency	~ 1.5 points
Low Heat Rejection Exhaust System	60 % heat loss reduction	~ 1.9 points
Low Friction/High BMEP	87% to 91% mechanical efficiency	~ 2.3 points
Burn Rate	20 degree to 18 degree 10 to 90% burn duration	~ 0.7 points
Flow Improvement	20% Improvement	~ 1.2 points
Two-Stage Compression w/ Intercooling	80% compressor efficiency per stage, 313 K intercooling	~ 0.4 points

Combination of the technologies above improves brake thermal efficiency from 40 to 50 percent

Some Key Technical Areas for Further Development

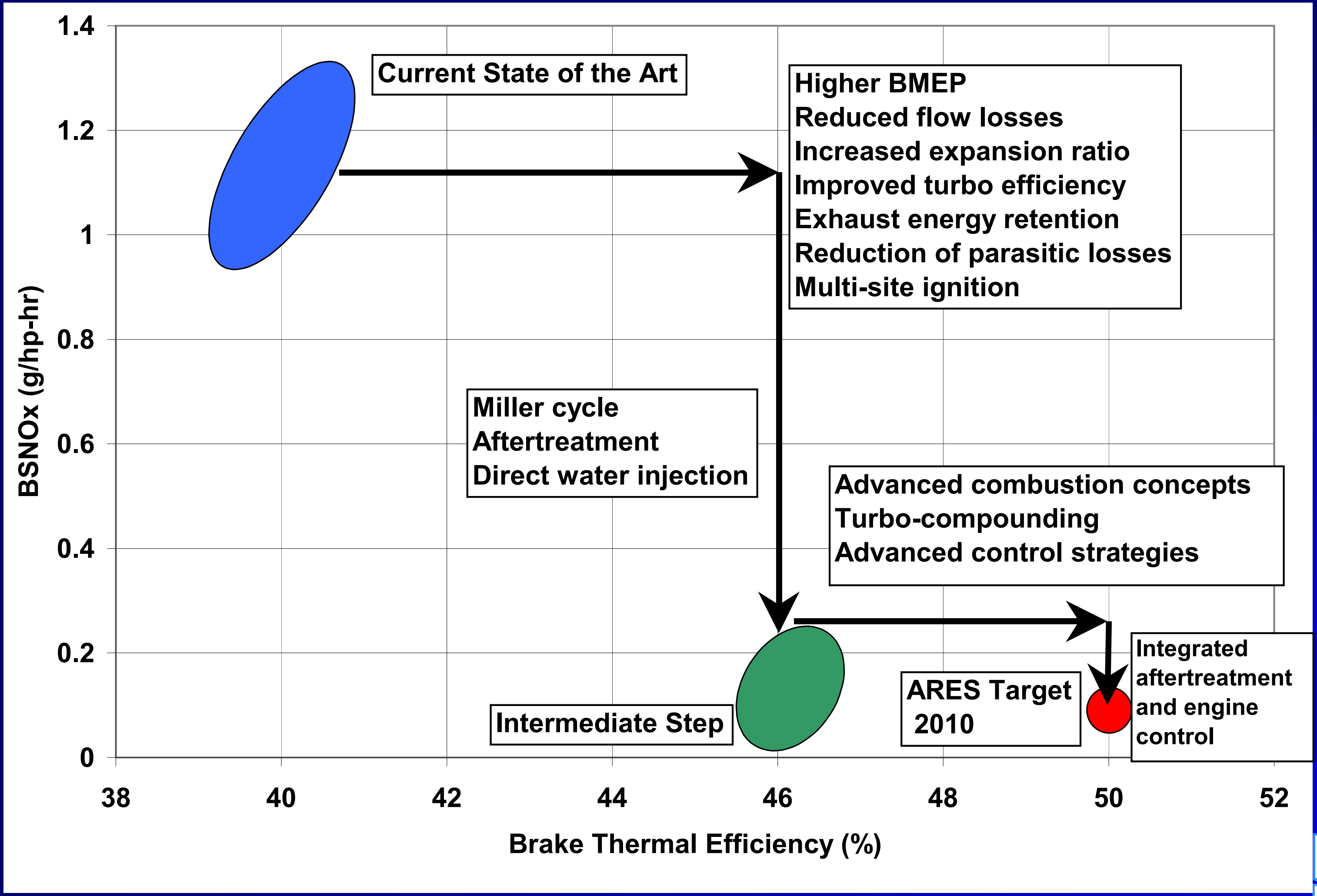


- Advanced combustion concepts
  - Designs for knock mitigation
  - Dilute combustion
- Continued development of advanced models
  - Fundamental testing to aid in model development
  - Burn rate and knock prediction
- Engine and exhaust aftertreatment control strategies and diagnostics
  - In-cylinder monitoring for knock and misfire
  - Integration of exhaust aftertreatment for ultra-low NOx emissions



- Ignition and combustion of dilute mixtures
  - Multi-site vs single vs distributed (HCCI)
- Exhaust aftertreatment technology
  - Durability of 3-way catalyst
  - Efficiency of technology for lean combustion
- Reduction of parasitic losses

We *can* get there from here!



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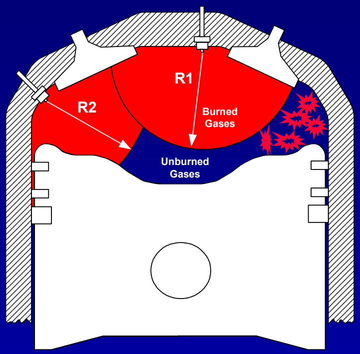
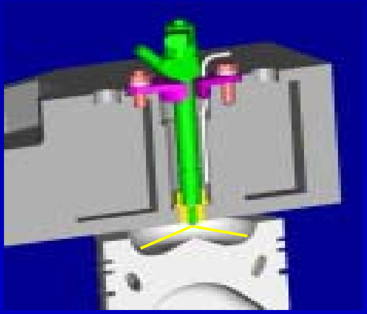
  - Southern California Gas
  - Altronic Inc
  - Federal Mogul - Champion
  - Woodward Governor
- ARES Team at SwRI
  - Too numerous to mention

Available ARES Tools

- **High Efficiency Gas Engine Models**
  - **ALAMO_Engine**
  - **RPEMS**
  - **GT Power Models**
- **Technology Tool Box**
  - **Dilute Combustion Systems**
    - Air as the Diluent
    - EGR as the Diluent
  - **Multi-site and Distributed Ignition**
  - **Knock Mitigation Strategies**
  - **Aftertreatment**
    - Heavy Duty 3-Way
    - Lean NO_x
    - SCR
  - **Integrated Control Strategies**
    - RPECS
    - RPEMS and Model Based Control
  - **High BMEP**
    - High Boost
    - Structural Analysis/Design
- **Large Engine Test Facility**





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Thank you for your attention!